Denali Commission

Emerging Energy Technology Grant

An Investigation of Psychrophiles for Generating Heating Gas in Arctic Environments

A Project by Cordova Electric Cooperation

Emerging Energy Technology Grant

Emerging energy technology is a critical phase in the development process of energy technology, linking research and development to the commercialization of energy solutions. Although the Arctic possesses bountiful energy resources, the Arctic also faces unique conditions in terms of climate, environment, population density, energy costs, logistics, and the isolated nature of electrical generation and transmission systems. These conditions, challenging under the best of circumstances, making the Arctic an ideal test bed for energy technology. Emerging energy technology provides a unique opportunity to meet Arctic energy needs, develop energy resources, and create global expertise.

In 2009 the Denali Commission, an independent federal agency in Alaska, released a public solicitation entitled the Emerging Energy Technology Grant (EETG). The EETG targeted (1) research, development, or demonstration projects designed to (a) test new energy technologies or methods of conserving energy or (b) improve an existing energy technology; and (2) applied research projects that employ energy technology with a reasonable expectation that the technology will be commercially viable in Alaska in not more than five years.

The following are the 9 projects funded under this solicitation:

Alaska SeaLife Center, Seawater Heat Pump Demonstration Project
Cordova Electric Cooperative, Psychrophiles for Generating Heating Gas
Kotzebue Electric Association, Feasibility of Solar Hot Water Systems
ORPC Alaska, Nenana Hydrokinetic Turbine
Sealaska Corporation, Commercial Scale Wood Pellet Boiler
Kotzebue Electric Association, Flow Battery Energy Storage Systems
Tanana Chiefs Conference, Organic Rankine Cycle Heat Recovery System
University of Alaska, Fairbanks, High Penetration Hybrid Power System
Kotzebue Electric Association, Wales Diesel-Off High Penetration Wind System

For further information, please visit the EETG program website at:

http://energy-alaska.wikidot.com/emerging-energy-technology-grant

Cordova Electric Cooperative

Originally the municipality of Cordova provided electric energy to the community. In 1978, the citizens of Cordova organized and voted to form a rural electric cooperative. These visionary citizens named the utility Cordova Electric Cooperative, and assumed member ownership and stewardship of the Cooperative. Cordova Electric Cooperative was energized on September 30, 1978. CEC currently serves 1,608 consumers, has 62 miles of line, one substation, and a generating capacity of 14.4 megawatts as follows: Orca Power Plant facility (diesel plant)-7.15 megawatts, Humpback Creek Hydroelectric facility-1.25 megawatts, and Power Creek Hydroelectric facility-6 megawatts.

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About the Author

The Alaska Center for Energy and Power (ACEP) is an applied energy research group housed under the Institute of Northern Engineering at the University of Alaska Fairbanks. ACEP is serving as the program manager of the EETG program on behalf of the Denali Commission.

A key deliverable for each EETG project is a lessons learned report by ACEP. As the projects deal with emerging energy technology, providing lessons learned and recommendations is critical for understanding the future of the technology in Alaska, and the next steps needed in developing energy solutions for Alaska.

ACEP's technical knowledge and objective academic management of the projects, specifically for data collection, analysis, and reporting, are vital components to the intent of the solicitation.

An Investigation of Psychrophiles for Generating Heating Gas in Arctic Environments

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Recipient:

Cordova Electric Cooperative

EETG Funding: $250,910

Total Project Funding: $347,012

Project Timeline:

October 2009—September 2011

Report Overview

Small-scale biogas digesters are commonly used throughout regions with tropical and subtropical climates: Southeast Asia, Central and South America, the Middle East, and Africa. Digesters are used to generate biogas, which is a mixture of methane, carbon dioxide, and other trace gases. Biogas can be used as a fuel for a number of different applications including cooking, heating, and running an electric generator. Typically, the methanogens responsible for biogas production are limited in application to warm environments. This project, which was funded by the Denali Commission Emerging Energy Technology Grant (EETG) program, investigated the development of biogas digesters in cold climates using recently discovered psychrophilic (cold loving) methanogens. The following report includes a project summary, a discussion of challenges, and recommendations for future projects and research.

For comprehensive project information, data, and report appendices, please visit the EETG program website at *http://energy-alaska.wikidot.com/emerging-energy-technology-grant*

Project Introduction

The goal of this project was to test the viability of small-scale biogas digesters in rural Alaska using psychrophilic methanogens, with the intent of displacing standard energy sources and reducing organic waste. The psychrophiles were collected from lakes in local areas. Since these methanogens evolved in arctic and subarctic climates, it is postulated that they could be used to generate biogas in cold regions similarly to how mesophilic methanogens produce biogas in warm regions. The project was divided into two phases:

Phase I

1. Construction of six 1000-L biogas digesters containing different methanogen cultures in two different temperature regimes.
2. Monitoring of physical and chemical characteristics of the digester environments.
3. Production and measurement of biogas.

Phase II

1. Demonstration and application of biogas and digester effluent.
2. Economic evaluation based on installation/maintenance costs and biogas production.

Project activities began with a small pilot study in November 2009. Phase I began with construction of biogas digesters in January 2010. The digesters were monitored beyond the conclusion of Phase I in March 2011. Phase II began immediately after Phase I was completed and ended in September 2011.

This collaborative effort included the following individuals and groups:

University of Alaska Fairbanks Laboratory Group

Katey Walter Anthony is a faculty member of the Water and Environmental Research Center at the University of Alaska Fairbanks (UAF) and the project's Research Director. Casey Pape, Laurel McFadden, and Peter Anthony were research technicians for the project. Dane McFadden was a project intern from Stanford University.

SOLAR Cities:

Founded by Thomas "TH" Culhane, SOLAR Cities is a non-profit that focuses on home-scale sustainable solutions in developing countries. A biogas expert, Culhane provided consultation and assistance in construction of the digesters.

Cordova High School (CHS)

The CHS provided a location for the biogas digesters. Adam

Low, a CHS science teacher, was responsible for guiding student involvement, and student volunteers with the CHS Science Club participated in construction, feeding, maintenance, demonstrations, and presentations.

Cordova Electric Cooperative (CEC)

The CEC provides electricity for the city of Cordova and was a local sponsor of the project. As the grant administrator, the CEC provided technical assistance and match-funding support.

Alaska Center for Energy and Power (ACEP)

An applied energy research program based at UAF, ACEP provided technical support for data collection. In addition, ACEP provided independent project and lessons-learned reporting on behalf of the Denali Commission. This report represents the final product of ACEP's effort.

Technology Background

Methanogenesis

Methanogenesis is a multistage biochemical process that involves several different types of bacteria and microbes and leads to the production of methane. The process begins with hydrolysis, in which long chains of organic compounds such as sugars, fats, and proteins are broken down chemically into simpler compounds. These simple organic molecules are then converted to acetic acid, hydrogen, and carbon dioxide by fermentative bacteria. The anaerobic methanogenic bacteria convert the acetic acid and hydrogen into methane. The product resulting from the bacterial interaction is biogas, which is composed of 40–70% methane, 30–60% carbon dioxide, and 1–5% other gases. The process is highly dependent on environmental conditions including temperature, pH, oxygen levels, and nutrient availability (Kossmann 1999). The energy density of biogas is lower than that of other fuels (Figure 1). Biogas, however, is typically easier to produce as it does not need industrial-scale extraction or refining techniques.

Fuel	Energy Content (MJ/kg)
Biogas (65% Methane)	20
Natural gas	48
Propane	46
Diesel	45

Figure 1. *Comparative Energy Content for Biogas and Other Typical Heating Fuels*

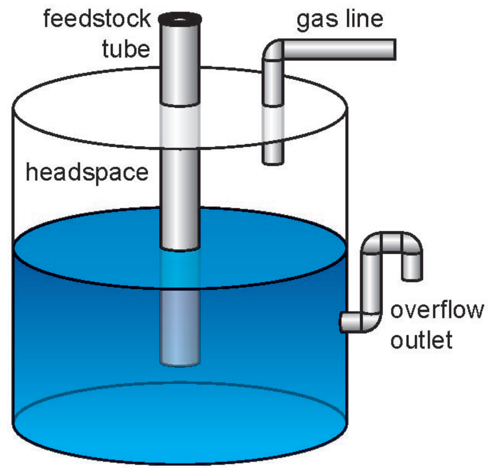

Figure 2. *Simple Residential-Scale Biogas Digester*

Biogas Digesters

The bacteria responsible for methanogenesis are naturally found in the digestive system of ruminant livestock and at the bottom of lakebeds and swamps. Ruminant fecal matter containing the bacteria is mixed with water and kept in biogas digesters for biogas production and harvest. Biogas digesters are primarily used to collect the biogas, which is then used for cooking, heating, lighting, or running an electric generator. A biogas digester is a large tank that is sealed to keep oxygen levels low (Figure 2). Although there are several openings in a biogas digester, the holes are designed to minimize oxygen mixing with the contents of the digester. A pipe coming from the headspace of the digester connects to a gas line to capture the biogas. A feedstock tube for adding nutrients directs food towards the bottom of the digester. The top of an overflow outlet is located near the top of the water line to allow the removal of effluent.

In addition to producing energy, biogas digesters aid in waste management, as the feed used by the digesters is typically food scraps or agricultural waste. The effluent from the digesters can be used as fertilizer (Kossman 1999). Biogas digesters are scalable. Large digesters are found in agricultural and water treatment facilities, and small digesters are found in single households or small communities (Kossman 1999).

Temperature Limitations

Currently, most biogas digesters use mesophilic (warm loving) methanogens and operate in temperatures of 20°–40°C.

There is a linear relationship (Hashimoto 1981) between the metabolism of methanogens and temperature in this temperature range, meaning that as temperature increases, methane production increases as well. Thus, a digester must be used in a warm climate or a heated environment; otherwise very little biogas will be produced. In recent years, however, Zimov (1997) and Walter (2006) have demonstrated that methanogenesis occurs in arctic and subarctic thermokarst lakebeds. These psychrophilic (cold loving) methanogens are capable of producing methane in relatively cold environments of 0°–20°C.

Project Review

This project focused on demonstrating the generation of biogas and the application of biogas digesters in Alaska's cold environment using psychrophilic methanogens. Three hypotheses were tested:

- Biogas digesters are more productive in a tepid environment (25°C) than in a cool environment (15°C);
- Psychrophiles outproduce mesophiles in both tepid and cool environments; and
- Less biogas is produced in tepid and cool environments than in a warm environments (35°–40°C).

Because of the expense of shipping fuel to remote locations, rural Alaskans could benefit from the use of psychrophiles as a supplemental energy source. The intent of this project was to demonstrate the successful use of biogas digesters in cold climates. Several small-scale (1000-L) digesters were constructed at a high school in Cordova, Alaska, and generated biogas was collected and used in demonstrative applications. The project had two phases: Phase I focused on the construction of digesters and the generation and measurement of biogas, and Phase II focused on the collection and application of biogas.

For comprehensive project information and reporting, please visit *http://energy-alaska.wikidot.com/psychrophiles-for-generating-heating-gas*

Phase I Summary

The goal of Phase I was to test and compare mesophiles and psychrophiles in cool and tepid conditions.

Project Setup

Methanogens were grown and kept in biogas digesters similar to the digesters already used in warm climates. Prior to Phase I, a pilot study was necessary to determine the amount

Figure 3. *Connex Container with 1000 L Water Tanks Before Being Converted into Biogas Digesters* Photo by Casey Pape

of lake sediment required to establish a methanogenic culture in a digester. A 9:1 ratio of water to lake sediment was found to be sufficient. During the pilot study, it was determined that there was no significant difference in microbe growth whether it occurred in chlorinated tap water or in the lake water from which the psychrophiles were harvested. At the start of Phase I, six 1000 L biogas digesters were constructed in a 40 ft Connex shipping container (Figure 3). The Connex was divided into two rooms: a cool room intended to be kept at 15°C and a tepid room intended to be kept at 25°C. Each room housed three digesters (Figure 4): one containing psychrophiles, one containing mesophiles, and one containing a mix of psychrophiles and mesophiles.

Systems were comprehensively monitored to gain a full understanding of environmental and production parameters for the digesters. Mean hourly temperatures were acquired for both rooms. In each digester, the pH, dissolved oxygen, oxidation-reduction potential, and temperature near the top and bottom of the tank were measured regularly. The gas flow out of each digester was also measured. Biogas samples were taken periodically and examined with a gas chromatograph to determine the concentrations of methane, carbon dioxide, and trace gases. Samples of the effluent were also taken to determine the concentrations of chloride, fluoride, nitrate, nitrite, phosphate, and sulfates.

Acidity Challenges

Within a couple weeks of construction, all but one of the digesters showed signs of biogas production; a flame was sustained on the gas outlets of the digesters. After the microbial colony was established, each digester began its feeding regimen, which consisted of 1 kg of food waste

Figure 4. *Three Biogas Digesters Inside the Connex*
Photo by Casey Pape

and 1 kg of water mixed together into a slurry. Feeding was conducted by the CHS Science Club. Once a week, the students prepared the necessary food and froze it for later use. This process took about two hours. Each day, the students thawed the food and put it into the digester.

About one month after feeding began, the pH of the digesters began to drop. Feeding was halted in March, and various chemicals were added to the tanks to return the pH to the required value of approximately 7. The necessary quantities of alkaline chemicals were calculated, and then added in small amounts over two months so as not to raise the pH too high. After the pH neutralized for all but one of the digesters, feeding was resumed. The pH began to fall again, so feeding was reduced to 0.5 kg of food and 0.5 kg of water for the remainder of the project. The pH stabilized for most of the digesters, though not the one with mesophiles in the cool room.

No measurable biogas production occurred in the cool room for the digester containing mesophiles and the digester containing a mix of mesophiles and psychrophiles, despite neutral pH in the mixed digester, so the feeding of those digesters was halted before the end of the project.

Gas Measurement

Once the pH problem was solved, effort was directed toward monitoring production. It was discovered that the amounts of gas being produced by digesters was too small for the calibration range of the flow meters. This problem was resolved by closing the valve at the headspace of the digesters and allowing pressure to build. Every six to eight hours, a project technician would manually open the valve and release the gas. Since the flow rate increased during biogas expulsion, the flow meters functioned as intended. Increased pressure also allowed the project team to more readily identify leaks in the system. Many leaks, particularly at the plumbing joints, were discovered, leading to refurbishment of the gas line.

Digester Environment and Content

The temperature measurements indicate that the rooms were not kept at a stable temperature, and that the room temperatures were highly dependent on the temperature outside. Likewise, the inside of the digesters followed the temperature of the room, though temperatures varied among the digesters within a room. The pH, dissolved oxygen, and oxidation-reduction potential were related to the overall health of a digester. When the pH dropped, oxidation-reduction potential increased. Dissolved oxygen levels remained low for the entire project.

Gas chromatography indicates that the average methane content of the biogas was 65% by volume, which is on the high end of the standard range of 40–70%. The digester effluent was measured using high-pressure liquid chromatography. The only detectable compounds were chlorides and phosphates. The modest phosphate content suggests that the effluent has potential for use as a fertilizer. The chloride content was a result of chloride in the tap water used in the digester feeding. The pilot study has shown that biogas production is possible, even in the presence of chloride

Phase I Results

In the tepid room, the average volume of biogas produced was 275 L per day by the psychrophiles, 173 L per day by the mesophiles, and 265 L per day by the mixed psychrophiles and mesophiles. In the cold room, the psychrophiles produced an average of 46 L of biogas per day, and the digesters containing mesophiles and both methanogens did not produce any measureable biogas. When viewed in conjunction with the energy content of the biogas, the energy production rate of the tepid room was 4–6 MJ per day per digester. As expected, much less biogas was produced in the cool and tepid temperatures maintained in this project than is typically produced in warm regions. Significantly more biogas was produced in digesters in the warmer room. Slightly more biogas was produced by the psychrophiles than the mesophiles in the tepid room; however, the average temperature of the psychrophile digester was higher than the mesophile digester.

The difference in production was more likely a result of temperature variations in the digesters than a difference in methanogenic cultures. The temperature variations were due to non-uniform insulation in the Connex. The results seem to indicate that despite their ability to produce methane in lower temperatures, the psychrophiles do not necessarily produce more methane than the mesophiles in temperatures hospitable to both. Difficulties in maintaining consistent temperature within the testing environment and between the digesters during experimentation limits the ability to make definitive conclusions regarding comparative production in environments with identical temperatures.

Phase II Summary

The focus of Phase II was on the techniques of biogas capture and application.

Biogas Collection Prototype

During the remainder of the project, much time was spent on developing a viable method for collecting and storing biogas in Alaska. A telescoping tank was designed and demonstrated (Figure 5). For the demonstration, a 1000-gallon high-density polyethylene (HDPE) tank with an open top was filled half way with water. A smaller 500-gallon tank with an open top was placed upside down into the larger tank to form an air gap. Biogas from the digester was fed into the headspace. When biogas was needed, a valve between the two systems was closed, and weight was added to the top of the tank to pressurize the gas.

Biogas Application Demonstration

Several applications of digester products were demonstrated. A cooking stove was modified to use biogas, and a pot of water was successfully brought to boiling in outdoor conditions. The stove used approximately 300 L per hour. A gasoline-powered 1850 W electric generator was converted to run on biogas. To be used as a fuel, biogas must be pressurized. The biogas was consumed at a rate of about 1100 L per hour.

Effluent Application Demonstration

In addition to producing biogas, digesters create effluent. Students used the effluent as liquid fertilizer in a qualitative experiment that was conducted in a greenhouse at CHS during the course of Phase I and II. The students found that flowering plants treated with the effluent tended to be larger and fuller than those treated with water. No noticeable size difference was apparent between crop plants treated with and without the effluent. In blind taste tests, it was determined that, with the possible exception of root vegetables such as carrots, the effluent did not negatively affect the taste of crop plants.

Decommissioning

In addition to the effluent experiment, the students at CHS

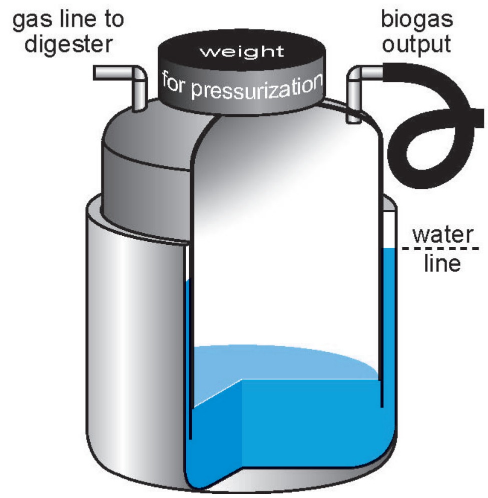

Figure 5. *Telescoping Biogas Storage Prototype*

conducted other experiments. They compared the calorimetry of biogas and propane, and investigated how to “clean” biogas by pumping it through calcium carbonate and filtering the carbon dioxide. Students assisted in conversion of the electric generator and other combustion engines to run on biogas. Some students presented their findings at the state science fair, the Rural Energy Conference, and the Alaska Forum on the Environment (Figure 6). Education and community involvement was an important aspect of the project, and the project team found the students' enthusiasm very encouraging. The contribution of the students was instrumental during the course of the project. Feeding of the digesters was primarily conducted by volunteers from the Science Club. This contribution was significant, as the technicians and engineers were needed for other aspects of the project.

Leading up to the end of Phase II, the temperature in both digester rooms was increased to 35°C and feeding was discontinued. These steps were taken to deplete as much of the nutrients as possible before deconstruction. After a few weeks, the effluent was completely drained from the digesters and disposed of. The digesters were disposed of at the waste compactor site. Most of the contents of the Connex storage unit were disassembled and given to CHS. The Connex was locked and remains at the school. The instrumentation and telescoping collection tank were disassembled and brought back to UAF.

Findings

Phase I verified that methanogens produce more biogas in warmer environments. Psychrophiles can produce methane at lower temperatures than mesophiles, but they do not necessarily produce more methane in mutually hospitable temperatures. Further research is required to verify comparative methate production in environments with identical temperatures. The methane content of the biogas produced was slightly higher than the methane content of the biogas from average digesters, meaning the energy content was slightly higher as well. This higher percentage of methane is not enough to offset the low production in cool or tepid climates. A single digester at approximately 25°C produces 4–6 MJ each day. This amount is comparable to about 110 g of diesel (0.04 gal), or 110 g of propane (2 cu ft). Typical digesters in warm climates produce approximately 21 MJ per day, which is equivalent to 0.58 L (0.15 gal) of diesel.

During Phase II, the project team demonstrated realistic applications of biogas as a fuel in Alaska. Biogas was used to run a cooking stove and an electric generator that had been converted to use gas. Potential applications extend beyond those demonstrated in Phase II. In addition to its use for cooking meals and running a generator, biogas can be used as heating fuel. A digester could alleviate waste disposal. Rather than putting food waste in the garbage, it can be used to feed a digester. The effluent still must be dealt with, but Phase II experiments showed that effluent can be used as liquid fertilizer.

The postulated advantage of psychrophiles over mesophiles to produce methane in cold temperatures does not assume outdoor siting for annual operation. Outdoor siting is fundamentally problematic as not only are low temperatures a concern for the productivity of methanogens, subzero temperatures pose a significant problem for the digester media and system. Psychrophiles in thermokarst lakes, for example, produce methane in a thermal regime insulated from below-freezing temperatures. Seasonal implementation of digesters is a theoretical option, but the short summers of cold regions and the lengthy start-up process involved in producing biogas would exacerbate the already poor economic incentives described later in these findings.

In Phase I, the original design kept the digester units in the weatherized Connex, although the pressurization system was stored outside the Connex due to lack of space and was rendered useless during winter months. The telescoping biogas collector prototype of Phase II sought to address winterization of that specific system component, presumably to allow for reduced energy costs associated with weatherizing the digester system. Although water was used in the demonstration, theoretically another fluid with a lower freezing point could be implemented, although project capital costs would increase (see next paragraph). Weatherized siting and associated energy costs are a requirement of biogas digesters in cold climates, assuming annual operation. Note that keeping a digester inside the living space is not necessarily an acceptable solution for most households, as the odors emitted by the digester and the effluent are unpleasant.

The Institute of Social and Economic Research (ISER) performed a Benefit-Cost Analysis and Sensitivity Analysis and compiled the findings into a report (Pathan 2012). The analyses showed that biogas digesters on a residential scale are not yet economically feasible for rural Alaska. About 57% of the overall cost of using biogas digesters is attributed to the labor needed to feed the digester, and about 25% of the overall cost is attributed to other maintenance labor. The tank and other parts represent approximately 9% of the total cost. The amount of potential fuel displaced by biogas is too small to offset the cost of installation, operation, and maintenance. If the digester can be developed into off-the-shelf technology, installation time and initial costs could be lowered. While there may be few economic incentives for the utilization of a residential-scale biogas digester, some households may choose to install a biogas digester for ecologic reasons, such as waste diversion, reduced carbon footprint, and a more sustainable lifestyle.

In addition to consideration of siting and economics, the end user should determine the approximate amount of food waste that would be produced in support of the digester. For small-scale biogas digesters, the standard daily feed rate for the digester is 1 kg of food mixed with 1 kg of water, though half of this total was found to be optimal for this project. If not enough food waste is generated per day, the end user would need to provide the digester with additional nutrients. Feed further increases the cost of a project that already has poor economic incentives. Another similar consideration before installation is the amount of labor needed to support a digester. The project team for this demonstration had the benefit of a large volunteer workforce in support of feeding.

It is important to note that biogas can be produced in ways other than with residential-scale digesters, and the methods may be more suitable for cold climates and/or more economically viable. Dairy farms, for instance, sometimes operate large-scale biogas digesters using the fecal matter of their cattle as a source of the methanogens and substrate for methanogenesis. This method has been demonstrated even in cool regions such as Vermont (Zezima 2009). Landfills often generate biogas that can be successfully captured and utilized. Biogas is currently recovered from the Anchorage Regional Landfill and used in power production for Joint Base Elmendorf-Richardson. Relevant to the methane

Figure 6. *Adam Low and CHS Students at the 2011 Alaska Forum on the Environment* Photo by Casey Pape

production process outlined in this report, the project team has explored capturing biogas where the psychrophiles originate: a thermokarst lake. The biogas is produced naturally, and in the winter is trapped underneath the ice. Further work is underway to investigate methods of extracting biogas from lakes and either using it on site or transporting it elsewhere.

This project successfully investigated and compared methane production by mesophiles and psychrophiles in cool and tepid conditions in Alaska and demonstrated potential applications of residential-scale biogas production. The involvement of students in the CHS Science Club was a model in terms of engaging youth in meaningful, innovative science and technology development (Figure 6). Although it was shown that residential-scale biogas digesters for cold climates are not economically viable at this time and that significant barriers prevent annual outdoor siting of system components, psychrophilic methanogenesis could be relevant for other types and/or scales of systems and applications in Alaska.

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i. http://ine.uaf.edu/werc/people/katey-walter-anthony/
ii. http://solarcities.blogspot.com/
iii. http://www.cordovaenergycenter.org/
iv. http://cordovaelectric.com/
v. It is assumed that "diesel" is equivalent to #2 heating oil. The values in the table were taken from the websites http://www.appropedia.org/Energy_content_of_fuels and http://www.baltic-biogasbus.eu/web/about-biogas.aspx
vi. Most biogas digesters use ruminant fecal matter as a source of methanogens, but similar bacteria can be found at the bottom of lakebeds.
vii. Thermokarst lakes are depressions in the landscape created and filled by thawing permafrost.
viii. The word psychrophilic can be divided into the prefix psychro-, meaning cold, and the suffix -philic, indicating affinity. Thermophiles have an affinity for hot temperatures and mesophiles have an affinity for mid-range temperature.
ix. In biogas digesters pH should be kept neutral, around 6.8–7.5. Dissolved oxygen levels need to remain as close to 0 as possible, because methane production is an anaerobic process. Oxidation-reduction potential (ORP) represents the ability of a compound to add or remove electrons in a solution, and should be around -300 mV. Chemical measurements were taken weekly. This project was testing for temperature dependence, so measured values were supposed to match the set temperatures.
x. In the beginning of the project, it was noticed that the digesters were becoming too acidic. This is a common occurrence in new biogas digesters. Feeding was stopped, and several basic chemicals were added to neutralize the digester. It is likely that the fermentative bacteria continued to produce acetic acid faster than the methanogens could metabolize the acid into methane. Patience is needed before starting a rigorous feeding schedule. The methanogens need time to develop before they can sustain stable methane production. The acidity problem was likely caused by more food than the bacteria could convert to methane at an adequate rate.
xi. Calcium carbonate (CaCO3), calcium oxide (CaO) and sodium hydroxide (NaOH).

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